Investigations into the Unexpected Delta-V Increases during the Earth Gravity Assists of Galileo and NEAR§

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Abstract

Because of the limited propulsive systems available for interplanetary trajectories to the outer planets and other solar system bodies, mission designers are utilizing the free exchange of potential energy from the planets such as Venus, Earth and Jupiter to spacecraft kinetic energy during gravity assists. During the first of two Earth gravity assists, the Galileo spacecraft experienced an unexplained net gain of 4.3 mm/s in December of 1990. This event prompted a thorough investigation of both the navigation software of the Navigation and Flight mechanics section at JPL and the mathematical models used for navigation. Other agencies such as the Goddard Space Flight Center and University of Texas have also investigated this discrepancy, but with no definitive explanation to the source of the ΔV. When Galileo returned to Earth in December 1992 for its second and final gravity assist, no anomalous ΔV appeared. However, an anomalous gravity-like signature did appear in the Doppler residuals. Interest in solving this puzzle had waned over the years, until the recent Near Earth Asteroid Rendezvous (NEAR) spacecraft's Earth gravity assist 'swing-by' on January 23, 1998. Like Galileo's first Earth gravity assist, NEAR also experienced a net gain of kinetic energy. This time it was 9 mm/s.

Some of the possible causes for the anomalous ΔV during the Galileo Earth-1 flyby such as flaws in the integration of the spacecraft trajectory or in the computation of the observations were investigated by Kallemeyn [1991]. Kallemeyn [1991] exonerated, to some extent, these possibilities as well as the necessary adjustments made to the Doppler observables such as media (troposphere and ionosphere) and spacecraft spin biases which affect the Doppler signal. Kallemeyn [1991] also dismissed the switching of Galileo's prime onboard antenna from the front Low Gain Antenna (LGA-1) to the rear LGA-2 during this flyby as the cause. This paper will further investigate the possible sources of these anomalous ΔV's beyond the work of Kallemeyn [1991]. These possible sources could be errors in the mathematical models representing the perturbing forces acting on the spacecraft while in the sphere of influence of Earth such as Earth's gravity field, relativistic effects, tidal effects, Earth radiation pressure or atmospheric drag. However, it will be shown that most of these perturbations such as atmospheric drag can be ruled out because of their brief exposure to the spacecraft's trajectory. Other sources that will further be examined include numerical round-off and integration errors. Errors in the spherical harmonic representation of Earth's gravity field will be examined by determining the coefficients most sensitive to the Galileo and NEAR hyperbolic orbits.

NEAR Earth Flyby Results

Figure 1 shows the X-band 2-way Doppler residuals for the NEAR Earth flyby. The data prior to the time of closest approach was used in the estimation of NEAR's orbit. Evidence of the net gain in energy is shown by the discontinuity between this data and the post-encounter data which was not included in this orbit estimation. This case shows an approximate 0.7 Hz shift in the Doppler measurements after closest approach. An impulsive ΔV of approximately 9 mm/s was estimated at the time of closest approach to remove this discontinuity given a spherical

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velocity *a priori* uncertainty of 100 mm/s. The direction of this ΔV was roughly in the direction of the spacecraft's geocentric velocity. All the Earth's high precision models including the 70 x 70 JGM-3 Earth gravity field have been included in the computation of the nominal trajectory.

Comparison of Galileo and NEAR Earth Gravity Assists

Table 1. compares the reconstructed hyperbolic orbit parameters for each of the three Earth flyby cases. It should be noted that the Galileo parameters are referenced with respect to Earth Mean Equator (EME) of 1950 and the NEAR parameters are with respect to EME-2000. Figure 2 shows the Earth groundtracks of each of the flybys.

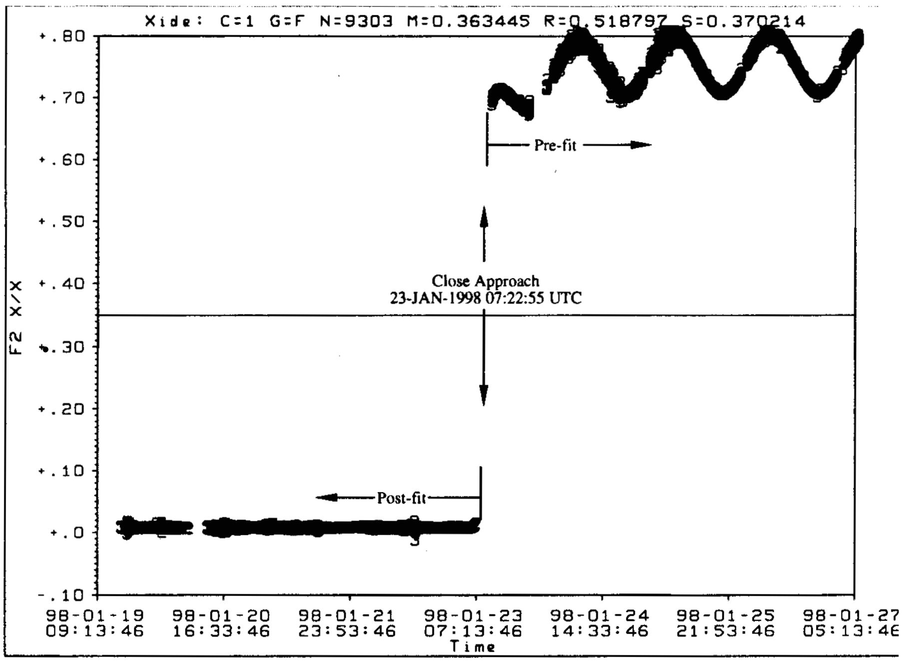

Figure 1: The X-band 2-way Doppler residuals during NEAR's Earth flyby.

Table 1: Comparison of the Hyperbolic Orbit Parameters during Galileo and NEAR Earth gravity assists

	Galileo Earth-1‡	Galileo Earth-2‡	NEAR†
B•R (km)	-6440.680	4474.826	-12133.305
B•T (km)	-9236.501	-9593.956	-4234.030
TCA (UTC)	8-DEC-1990 20:34:34.4	8-DEC-1992 15:09:24.9	23-JAN-1998 07:22:55.6
Altitude (km)	959.947	303.108	538.833
Longitude (East)	296.5 E	354.42° E	47.21° E
Latitude	25.2° N	-33.76° S	32.96° N
V_∞ (km/s)	8.949	8.877	6.851
Semi-major Axis (km)	-4977.034	-5057.776	-8493.326
Inclination	143.215°	138.657°	107.97°
Eccentricity	2.47	2.32	1.81
Deflection	47.69°	51.07°	66.92°
Anomalous ΔV (mm/s)	+4.3	0.0	+8.9

‡ With respect to EME 1950
† With respect to EME 2000

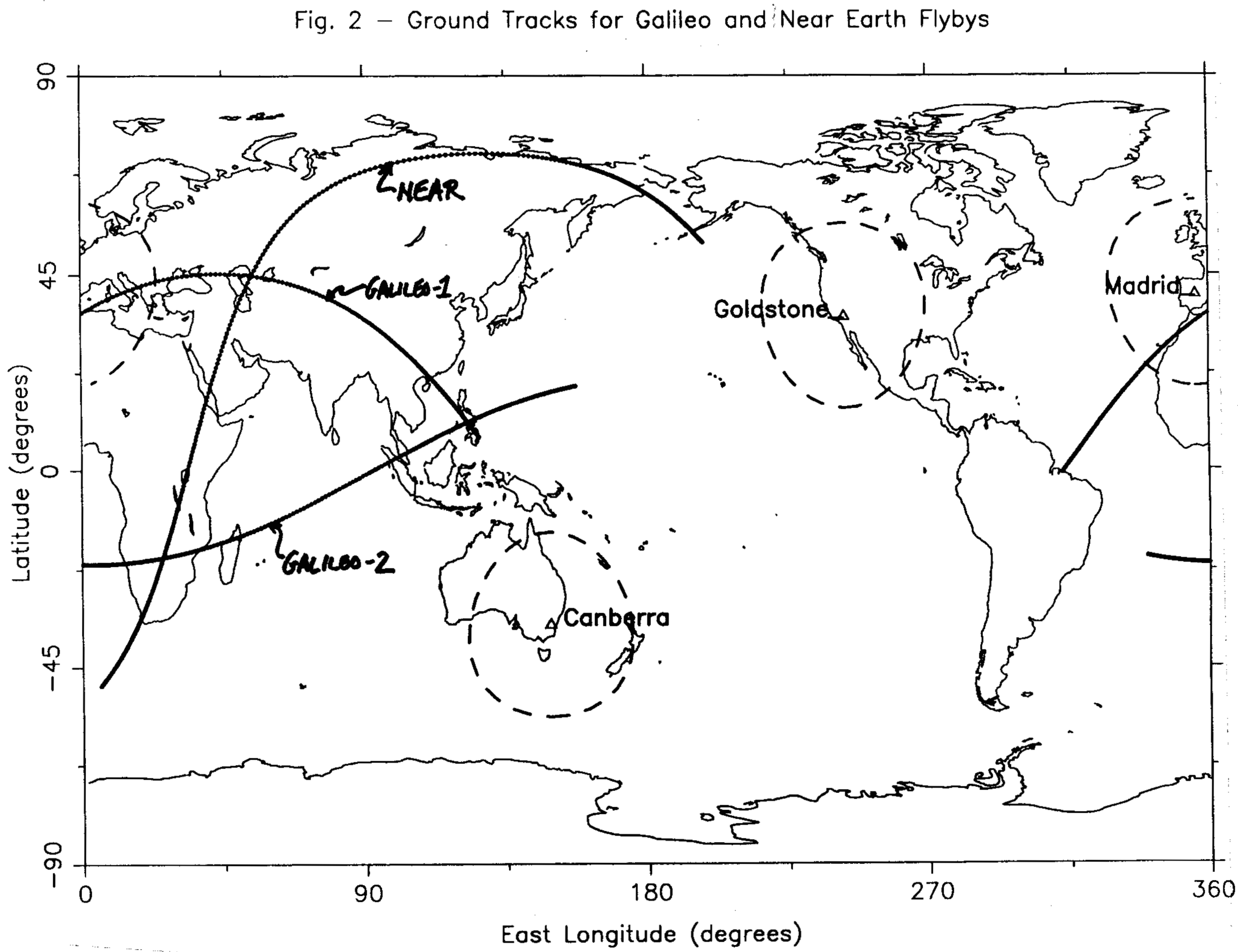

Figure 2: Comparing the ground tracks for Galileo and NEAR Earth flybys

REFERENCES

Kallemeyn, P., "Observations from Galileo Earth-1 Flyby Reconstruction Efforts," JPL Interoffice Memorandum, GLL-NAV-91-62, April 2, 1991.